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ELECTROWEAK FLAVOR-CONSERVING GAUGE PROCESSES: VIRTUAL EFFECTS*

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ABSTRACT

The electroweak Standard Model is summarized at the classical and quantum levels, including its gauge symmetry and symmetry-breaking aspects. The full implications of precise measurements of electroweak gauge forces are presented in terms of electroweak parameters and quantum corrections. The minimal Standard Model (SM) (including the top quark) satisfies the data well, up to one-loop accuracy. Possible non-Standard states subject to electroweak forces in quantum corrections is highly restricted by the present data. The status of exact and approximate symmetries of the electroweak Standard Model is summarized.

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Experiments

1. Electromagnetic Fine Structure Constant $\alpha_{\rm em}$

This parameter is the basic input to both quantum electrodynamics and the electroweak Standard Model and is best defined at energies well below electron-positron production threshold, so that relativistic field theoretical effects are unimportant [1]. It can be measured in a variety of ways, including methods of atomic, condensed matter, and low-energy scattering experiments. The best determinations of $\alpha_{\rm em}$ are made in macroscopic quantum Hall effect or AC Josephson junction experiments, yielding [2]:

$$\alpha_{\rm em}^{-1} = 137.0359895 \pm 0.0000061 \quad ,$$

accurate enough for the purposes of high-energy physics measurements.

2. Muon Decay and the Fermi Constant

The fundamental constant characterizing the strength of the weak interactions is the *Fermi constant,* G_μ, derived from the measured decay lifetime of the muon in the beta process $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ [3, 4] :

$$\tau_\mu^{-1} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} F(m_e^2/m_\mu^2)(1 + 3m_\mu^2/5M_W^2)[1 + \frac{\alpha(m_\mu)}{2\pi}(\frac{25}{4} - \pi^2)] \quad ,$$

where:

$$F(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \quad ,$$
$$\alpha(m_\mu)^{-1} = \alpha^{-1} - \frac{2}{3\pi}\ln(m_\mu/m_e) + \frac{1}{6\pi} \quad ,$$

with $\tau_\mu = (2.19703 \pm 0.00004) \times 10^{-6}$ sec, $G_\mu = (1.16639 \pm 0.00002) \times 10^{-5}$ GeV^{-2}, and $m_\mu/m_e = 206.768$ [4]. This relation involves only electromagnetic radiative corrections [5]. From G_μ can be extracted a universal weak decay constant G_F, after the application of the remaining, purely weak radiative corrections. This constant G_F is related to the Higgs vacuum expectation value (VEV):

$$\langle\phi\rangle^2 = 1/\sqrt{2}G_F \quad ,$$

so that $\langle\phi\rangle \simeq 246$ GeV sets the energy scale for the weak interactions and the electroweak symmetry breaking.

3. Deep Inelastic Neutrino Scattering

The 1980s saw a series of νN (neutrino-nucleon) deep inelastic scattering (DIS) scattering experiments, carried out by the CDHS [6] and CHARM [7] collaborations (CERN) and the CCFR collaboration (FNAL) [8], yielding measurements of $\sin^2\theta_W$ with accuracies to a few percent. These measurements are conventionally quoted, for theoretical convenience, in terms of the on-shell definition and are especially sensitive to the top quark mass m_t.

The experiments are based on the scattering of high-energy neutrino beams (100-200 GeV) off of fixed nuclear targets, in the *deep inelastic* regime; that is, the momentum transfer is large (compared to the nucleon mass) and spacelike, and the nucleon is transformed into a shower of hadrons. In this regime, the neutrinos couple directly to the underlying quarks (partons) of the nucleon, rather than to the nucleon as a whole. The scattering events are of two types, neutral (NC) and charged current (CC). The first is mediated by the Z and leaves the neutrino unchanged: the second is mediated by the W and transforms the neutrino into its charged lepton partner. Since the neutrino beams are obtained from muon decays, the (anti)neutrinos used are of the muon type, ν_μ or $\bar{\nu}_\mu$ [9,10].

The basic quantity of interest is the ratio of NC to CC ν_μ events, $R_\nu = \sigma_{NC}(\nu)/\sigma_{CC}(\nu)$. At the classical level, this ratio, in terms of $\sin^2\theta_W$, is:

$$R_\nu = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W(1+r) \quad ,$$

where $r = \sigma_{CC}(\bar{\nu})/\sigma_{CC}(\nu)$ requires the use of an antineutrino beam. Although a nucleon is, at the level of valence quarks, made up of only up (u) and down (d) quarks, it also contains a sea of virtual quark-antiquark pairs of all types, suppressed by their masses. Because of the presence of strange (s) quarks and Cabibbo mixing between the first and second families of quarks, the CC mode of νN scattering involves the production of heavy charm (c) quarks; e.g.,

$$\nu_\mu + d \to \mu^- + c \quad , \quad \nu_\mu + s \to \mu^- + c \quad ,$$

where the first is Cabibbo-suppressed and the second is the sea contribution. The cross section for this process involves the c mass m_c, thus introducing an uncertainty. The charm-mass threshold effect is usually modelled using the *slow rescaling* method that introduces an unknown, effective m_c.

The CHARM collaboration of CERN measured νN scattering, yielding a result for $\sin^2\theta_W = 0.236 + (0.012)(m_c - 1.5) \pm 0.005(\text{exp}) \pm 0.003(\text{th})$, with the effective $m_c = 1.5 \pm 0.3$ in GeV [7]. The CDHS collaboration of CERN measured $\sin^2\theta_W = 0.225 + (0.013)(m_c - 1.5) \pm 0.005(\text{exp}) \pm 0.003(\text{th})$, with the same m_c derived from an earlier CDHS experiment [7].*

The most recent reported result for neutrino-nucleon DIS is that of the CCFR collaboration at Fermilab, with $\sin^2\theta_W = 0.2218 \pm 0.0025(\text{stat}) \pm 0.0036(\text{syst}) \pm 0.0040(\text{th})$. The value of m_c was measured, rather than assumed, from the observation of dimuon events: $\nu_\mu + s \to \mu^- + c$, then $c \to s + \mu^+ + \nu_\mu$. The effective $m_c = 1.31 \pm 0.24$ GeV [8].

The combined weighted average of all DIS experiments yields $\sin^2\theta_W = 0.2260 \pm 0.0048$ [4].

The next neutrino-nucleon DIS experiment, probably the last significant improvement in such measurements, will be the Fermilab E815 experiment by the NuTeV collaboration, a descendant of CCFR, scheduled to begin in late 1995, with preliminary results by early 1997. Its goal is the measurement of $\sin^2\theta_W$ to ± 0.0025, with the unique feature of eliminating the charm threshold uncertainty. The measured quantities will be $R_\pm$:

$$\begin{aligned} R_\pm &= \frac{\sigma_{NC}(\nu) \pm \sigma_{NC}(\bar{\nu})}{\sigma_{CC}(\nu) \pm \sigma_{CC}(\bar{\nu})} \\ &= \frac{R_\nu \pm r R_{\bar{\nu}}}{1 \pm r} \quad , \end{aligned}$$

* The values of $\sin^2\theta_W$ here are adjusted for $m_t \simeq 180$ GeV.

using both neutrino and anti-neutrino beams. The m_c dependence of r has been measured by the Fermilab experiments E774 and E770. R_- is independent of charm production, depending only on valence quarks; with a fixed ρ, $\sin^2\theta_W$ can be extracted from R_-. (There is a small charm production in R_- from d quarks, with Cabibbo suppression $\sin^2\theta_C$.) With r known, R_ν and $R_{\bar{\nu}}$ can be inferred from R_+, whence, combined with R_-, independent values of ρ and $\sin^2\theta_W$ can be derived [11].

4. Neutrino-Electron Scattering

The leptonic analogue to DIS is (anti)neutrino-electron scattering. Two older experiments of this type are those of the CHARM I (CERN) [12] and E734 (BNL) [13] collaborations.

The best and most recent of these measurements was that performed by the CHARM II collaboration (CERN) [14]. The relevant quantities are the neutrino and antineutrino neutral current scattering cross sections and their ratio, $R = \sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e)$. The neutrinos were produced from muon decay and scattered from a fixed target. The ratio R allows a determination of $\sin^2\theta_W$, while the two separate cross sections allow a determination of the ρ parameter as well as the weak mixing angle. In the $\overline{MS}$ scheme, $\sin^2\hat{\theta}_W(M_Z^2) = 0.237\pm0.010(\mathrm{exp})\pm0.002(\mathrm{th})$, and $\hat{\rho} = 1.001\pm0.038(\mathrm{exp})\pm0.004(\mathrm{th})$ [4].

In the on-shell definition, the combined weighted average of all experiments (CHARM I, CHARM II, E734) yields: $\sin^2\theta_W = 0.224\pm0.009$.

5. W and Z Gauge Boson Properties

The values of the W and Z gauge boson masses and widths are quoted here in the on-shell renormalization scheme.

The measurement of the W gauge boson properties from direct production has been performed by the UA1 [15] and UA2 [16] collaborations of CERN and the CDF [17] and D0 [18] collaborations of Fermilab. The combined world average of the W mass is $M_W = 80.23\pm0.18$ GeV, with a combined world average W width of $\Gamma_W = 2.076\pm0.077$ GeV [19]. The W width is measured by both direct counting of decays and by examining ratios of partial widths of W to Z decays, combined with Z partial widths measured separately (see below).

The next group of measurements of the W boson properties are planned for CDF and D0 (Fermilab) and LEPII (CERN). The CDF/D0 program is one of continuing improvement, starting from Run I (1992-93) of 75 pb^{-1} to 200 pb^{-1} by 1997. With the Main Injector operating (scheduled 1998), the subsequent Run II is projected to accumulate several hundred pb^{-1}. More speculative is Run III, starting approximately in 2004, accumulating perhaps as much as 5 fb^{-1}. The projected error in M_W by the end of Run II is 50 MeV, limited at that point by systematics, with a comparable error in Γ_W [20]. LEPII is scheduled to begin operations by 1997 and to reach, by 2000, an accuracy in M_W and Γ_W of 30-50 MeV [21].

The bulk of the precision measurements of the Z boson properties come from the four experiments (ALEPH, DELPHI, OPAL, L3) at the LEP e^+e^- collider at CERN, which has been in operation since 1989 and has accumulated about eight million Z events [4,22,23].

The basic process is $e^+e^- \to Z$, decaying to final-state pairs of leptons and quarks. The Z mass and width are now measured to 91.189±0.004 GeV and 2.497±0.004 GeV, respectively. The LEP collaborations have measured a variety of asymmetries: forward-backward asymmetry $A_{FB}(Z)$ to leptonic and bottom and charm quark final states, and the τ and e polarization asymmetries $A_{\tau,e}(Z)$ (asymmetry to left- and right-handed τ, e). In addition, the hadronic-to-leptonic and the bottom- and charm-to-hadronic width ratios have been measured, with implications for the strong coupling $\alpha_s(M_Z^2)$ and virtual top quark effects in the $Z \to b\bar{b}$ vertex. The asymmetries are, in effect, measurements of an effective $\sin^2\theta_W$, essentially the Kennedy-Lynn $s_*^2(Z)$ [5] plus weak vertex corrections: $\sin^2\theta_W^{eff} =$ 0.2323±0.0002(exp)±0.0002(th). A LEP-only fit for m_t yields $m_t = 181\pm14$(exp)±20(th) GeV, including the two-loop $\mathcal{O}(\alpha\alpha_s)$ QCD correction [22], in good agreement with the CDF direct production result, $m_t = 174\pm16$ GeV [24]. The theoretical uncertainties are due to the unknown Higgs boson mass. The width measurements are all in agreement with the SM predictions, with the exception of the $Z \to b\bar{b}$ partial width, which is 2.2σ above the SM prediction.

The SLC e^+e^- collider at SLAC has a unique ability to polarize its electron beam and thus to measure the left-right polarization asymmetry $A_{LR}(Z)$, the difference of Z production with left- and right-handed initial electrons. The SLC collider commenced operations in 1989, but did not begin polarized measurements until 1992. Slightly fewer than 50,000 polarized events have been accumulated, with average polarization (66±1)%, but certain features of $A_{LR}(Z)$ compensate for this smaller data sample, in comparison with the LEP asymmetry measurements. Through 1993, the SLD collaboration has measured $\sin^2\theta_W^{eff} = 0.2294\pm0.0010$, which is 2.8σ below the LEP result, an as-yet unexplained discrepancy [4,23,24].

LEP is scheduled to run until the end of 1995, with projected improvements in: $\sin^2\theta_W$ to 0.0003, Γ_Z to 2 MeV, and Γ_Z^{bb} to 0.5% . A polarization measurement at LEP has been proposed for 1996, which, if carried out, could yield a measurement of $\sin^2\theta_W$ to 0.0001 [26]. The next polarization run at SLC, starting in 1994, is projected to produce 100-150,000 polarized Z events, with a consequent accuracy in $\sin^2\theta_W$ of 0.0005 [27].

6. *Hadronic Decay* $Z \to b\bar{b}$

This flavor-specific decay mode is, at the Z pole, uniquely sensitive to physics involving heavy fermion masses, as the b quark is in the third family. The deviation of this quantity from its Standard Model value is not in the same class as the S, T, U corrections, because it is not universal to all fermion final states of the Z. Rather, the decay width depends on the special $Z \to b\bar{b}$ vertex, which receives additional heavy top quark mass corrections beyond the universal T correction [4,5]. The measurement from CERN/LEP is extracted from the branching ratio $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to hadrons)$. This ratio is at present 1.8σ above its Standard Model prediction. With

$$\Gamma(Z \to b\bar{b}) = \Gamma^0(Z \to b\bar{b})(1+\gamma_b) \quad ,$$

where $\Gamma^0(Z \to b\bar{b})$ includes the universal S, T, U, and ρ_0 corrections, we have, for non-Standard contributions:

$$\gamma_b^{NS} = 0.032 \pm 0.016 \quad .$$

In the SM,

$$\gamma_b^{t\bar{t}} \simeq -(0.01)[\frac{m_t^2}{2M_Z^2} - \frac{1}{5}]$$

has already been removed to obtain the result γ_b^{NS} by using the CDF value of m_t.

This measurement can be used to place a $T-$ and $\rho-$independent constraint on the top quark mass of $m_t = 175\pm 16$ GeV [4].

7. Rare Z Gauge Boson Decays

Decays of the Z gauge boson with small branching ratios can be divided into three categories. The first consists of rare decays expected within the Standard Model; the second, of strictly forbidden decays with only Standard Model states; and the third, of decays with non-Standard particles. The last class is necessarily as aspect of new, non-Standard particle searches and is not discussed here. Of the accelerators that have produced Z bosons (Sp$\bar{\text{p}}$S, Tevatron, SLC, LEP), only LEP has produced Z events in numbers sufficient to make study of rare Z decays possible.

The LEP collaborations have studied the Standard Model rare processes $Z \to \gamma\gamma\gamma$, $Z \to \gamma + PS(V)$ (with $PS(V)$ = pseudoscalar or vector meson), $Z \to \gamma^* \nu\bar{\nu}$ (with $\gamma^* \to f\bar{f}$), and $Z \to \gamma\gamma f\bar{f}$ [4,23]. The first two searches have found rates consistent with the Standard Model. The third search recorded events in excess of expectation, but still allowed at the 5% level. The status of final search is unclear, as the L3 collaboration found four such events with invariant $\gamma\gamma$ mass of about 60 GeV, more than a factor of ten greater than the Standard Model expectation, suggesting associated production of a state X in the Z decay, with $X \to \gamma\gamma$ and $m_X \simeq 60$ GeV. However, subsequent DELPHI searches have found no invariant $\gamma\gamma$ peak at this energy and no inconsistency with the Standard Model.

The LEP experiments have also been used to search for the strictly forbidden decays: $Z \to e\mu, e\tau$, and $\mu\tau$, and $Z \to pe$ (or μ). The first set violates the separate lepton family numbers, which, in the absence of neutrino masses and mixings, are exactly conserved. The second violates baryon and lepton numbers. Both searches have found no evidence for such decays.

8. Atomic Parity Violation

A number of atomic parity violation (APV) experiments before 1988 reported results for $\sin^2\theta_W$; however, the completion of the cesium measurement at the University of Colorado, Boulder, of Wieman *et al.* in 1988 raised the experimental precision of APV to a significantly higher level. Their result for the atomic *weak charge* $Q_W^{Cs} = -71.04\pm 1.58(\text{exp})\pm 0.88(\text{th})$ [28]. The atomic theory calculation was carried out by Sapirstein *et al.* in 1990 [29]. Combined with M_Z measured at LEP, this APV measurement alone yields an unusually negative value of $S \simeq -3$ [30], albeit with a large uncertainty $\simeq \pm 4$. The measurement is performed with atomic transitions in crossed electric and magnetic fields.

Wieman's group at Boulder is proceeding with an improved cesium measurement, whose goal is an uncertainty in Q_W^{Cs} of $\pm 0.30 - 0.35$, with a plan comparable uncertainty in atomic theory, calculated again by Sapirstein *et al.* The new experiment will use laser-trapped cesium atoms and, by using different isotopes of cesium, can eliminate some of the

atomic theory uncertainty. This effort is scheduled to be completed in 3-4 years, yielding a reduced uncertainty in S measured by APV alone of $\simeq \pm 1$ [31,32].

A more recent program of APV is being conducted by Norval Fortson *et al.* of the University of Washington, Seattle, based on optical rotation of polarized light in lead and thallium vapors. This group has published an APV measurement in lead with $\pm 1\%$ accuracy, the best so far [33]. The atomic theory, unfortunately, has uncertainty of approximately $\pm 8\%$ [34]; much of this uncertainty can be eliminated by the use of different lead isotopes, as planned by the Fortson collaboration in the coming years. A better measurement has been done in thallium, for which a fairly precise calculation has been done, to $\pm 3\%$. The experimental uncertainty is again $\pm 1\%$, yielding S = -2.3$\pm$3.2; the final experimental uncertainty should reach approximately $\pm 0.5\%$ [35]. Sapirstein *et al.* [32] and Martensson-Pendrill *et al.* [36] are calculating the atomic theory for thallium. The Fortson group is also beginning to explore the use of trapped single atomic ions for APV measurements; for example, Ba^+, similar to cesium [35].

Summary of Future Experiments

Between this year (1994) and 2000, the subject of precision measurements of electroweak gauge interactions will be refined into its probable final form.

- The W boson mass M_W will be measured to approximately ± 50 MeV by the CDF and D0 collaborations at the Tevatron (Fermilab), and to $\pm 30 - 50$ MeV at LEPII (CERN).
- The top quark mass will be measured to $\pm 5 - 10$ GeV by CDF and D0 [37].

These two measurements require the Main Injector at Fermilab, which is scheduled to operate in 1998 [20]; while LEPII is scheduled to begin operations in 1996/97 [26].

- The NuTeV collaboration's E815 experiment at Fermilab will have measured $\sin^2\theta_W$ to ± 0.0025 by 1998 by DIS [11].
- The Boulder and Seattle APV measurements will result in an S measurement to approximately $\pm 1 - 1.5$.
- In the next two years, the SLD collaboration at SLC/SLAC will complete their measurement of $A_{LR}(Z)$ with 3-500,000 polarized Z events at approximately 80% polarization, with a result for $\sin^2\theta_W$ accurate to ± 0.004 [27].

If the top quark mass is known to better than ± 10 GeV, the electroweak SM can be tested with negligible uncertainty to the one-loop level of perturbation theory [4,5]. Together with improved measurements of flavor-mixing and CP violation, gauge interactions and the fermion mass matrix will be available in essentially complete form. Any deviations of measurements from the minimal SM, with known top quark mass, will provide clear evidence for heavy particle states beyond the Z mass and place constraints on the possible realizations of the Higgs sector. The presently available data already disfavor additions to the minimal SM, unless of a special type that produces small to no effects below the Z pole. A supersymmetric Higgs sector, with the superpartners of known particles, matches the data well [4,5], while strongly coupled Higgs sectors such as technicolor are difficult to accommodate. However, real knowledge of the Higgs sector requires direct exploration with very high energy accelerators.

Electroweak Gauge Theory

The electroweak Standard Model is a non-Abelian gauge theory based on the gauge group $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ [5,9,10,38]. The gauge symmetry is broken by the Higgs sector, leaving an unbroken Abelian gauge group $\mathrm{U}(1)_Q$, the basis of quantum electrodynamics (QED) with its massless photon (γ). The other three gauge bosons, the charged $W^{\pm}$ and neutral Z°, are massive, with masses of approximately 80 and 91 GeV/c^2, respectively; these mediate low-energy Fermi four-fermion weak interactions, such as beta decay and neutrino-nucleon scattering. The underlying gauge couplings, the $\mathrm{SU}(2)_L$ g and the $\mathrm{U}(1)_Y$ g', are small, allowing perturbative expansion in powers of the couplings as a solution of the quantum theory. Non-perturbative solutions of the electroweak gauge theory have also been investigated, including the so-called *sphalerons* [39] (please see the report of Working Group 6: Astroparticle Physics, Cosmology, and Unification), but these are not relevant to accelerator experiments.

At tree (classical) level, the electroweak gauge theory has four parameters, equivalent to g, g', $\langle\phi\rangle$, and ρ. The electromagnetic coupling $\alpha = e^2/4\pi$, the Fermi weak decay constant G_F, the sine of the weak mixing angle $\sin^2\theta_W$, and the weak gauge boson masses M_W and M_Z are then:

$$\begin{aligned}
\alpha_{\rm em}^{-1} &= 4\pi/e^2 = 4\pi[1/g^2 + 1/g'^2] \quad , \\
\tan\theta_W &= g'/g \quad , \\
G_F &= 1/\sqrt{2}\langle\phi\rangle^2 \quad , \\
M_Z^2 &= \frac{\pi\alpha}{G_F \sin^2\theta_W \cos^2\theta_W} \quad , \\
\rho &= M_W^2/M_Z^2\cos^2\theta_W \quad .
\end{aligned}$$

If the Higgs VEV is due solely to $\mathrm{SU}(2)_L$ doublets, then $\rho = 1$ automatically. Once higher-order quantum or loop corrections are introduced, then the theory must be renormalized, and a set of arbitrarily but consistently defined parameters, a *renormalization scheme,* must be introduced to replace the classical parameters. The quantum or radiative corrections fall into two categories, *universal* and *non-universal;* that is, corrections that shift the value of the classical parameters without changing the form of classical interactions versus corrections that do not respect the classical form. The first type of corrections have been investigated in the work of Kennedy and Lynn [5], and Degrassi and Sirlin [40], and can be related to standard renormalization schemes. The second type of corrections varies depending on the specific process in question. All information concerning electroweak interactions is currently derived from four-fermion processes. Three renormalization schemes are commonly used, the *on-shell,* the *modified minimal subtraction* ($\overline{MS}$), and the *Lynn-Peskin-Stuart (LPS)* schemes. The on-shell weak mixing angle is defined by

$$\sin^2\theta_W = 1 - M_W^2/M_Z^2 \quad ,$$

while the $\overline{MS}$ $\sin^2\hat{\theta}_W(M_Z^2)$ is a running, scale-dependent weak mixing angle defined through the $\overline{MS}$ regularization method. It is particularly convenient for comparing electroweak measurements at differing energies and Z pole measurements with models of grand unification of electroweak and strong forces. Please see the report of Working Group 1: Tests of the Electroweak Theory, for further details. The calculation of the perturbative quantum field theory of electroweak interactions has been advanced and essentially completed over the last twenty years by many workers, including: Veltman, 't Hooft, Taylor,

Passarino, Marciano, Sirlin, Lynn, Stuart, Hollik, Jegerlehner, Jadach, Berends, Kleiss, B. F. L. Ward, Kennedy, Peskin, Takeuchi, and others.

For the purposes of investigating states and interactions beyond the SM, the crucial property of electroweak gauge theory is that the full gauge symmetry $\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$ is broken by the Higgs VEV [5]. This is necessary for the appearance of *non-decoupled* radiative corrections, which do not vanish as inverse powers of heavy particle masses M^2, in a process of a given momentum transfer q^2, with $M^2 \gg q^2$. Such effects scale as M^n ($n=0$ or 2) or $\ln(M^2)$. A further necessary condition is that the virtual effect break a tree-level global symmetry; these two conditions together are sufficient to produce non-decoupled effects. For flavor-conserving or -diagonal processes, the relevant global symmetries are the weak chiral group $\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R$ and its vector subgroup $\mathrm{SU}(2)_V$. Three conventional parameters, usually represented as S, T, and U, summarize completely universal non-decoupled effects in electroweak gauge interactions. The first, S, breaks the global $\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R$ group, while the last two, T and U, break the global $\mathrm{SU}(2)_V$ subgroup. In the case of a general, non-doublet Higgs sector, the classical parameter ρ replaces T : $1-\alpha T \to 1/\rho$. Complete one-loop calculations of S, T, and U have been performed for the minimal SM, as well as for the minimal SUSY SM and many technicolor theories. Without special cancellations, non-Standard physics is expected to contribute to these parameters at $\mathcal{O}(0.1-1)$, apart from group theoretical factors.

A summary of classical parameters:

$$\begin{aligned}\alpha_{\rm em}^{-1} &= 137.0359895 \pm 0.0000061 \quad ,\\ G_\mu &= (1.16639 \pm 0.00002)\times 10^{-5}\ \mathrm{GeV} \quad ,\\ M_Z &= 91.189 \pm 0.004\ \mathrm{GeV} \quad ,\\ \rho_0 &\equiv 1 \quad ,\end{aligned}$$

in the minimal, doublet-only Higgs case; otherwise [4,5]:

$$\rho_0 = M_W^2/\hat{\rho} M_Z^2 \cos^2\hat{\theta}_W(M_Z^2) \quad ,$$

with $\hat{\rho}^{-1} \simeq 1-\alpha T$. A global fit to all current and relevant electroweak data yields, in the minimal SM with doublet-only Higgs VEVs (May 1994) [4]:

$$\begin{aligned}\sin^2\hat{\theta}_W(M_Z^2) &= 0.2317 \pm 0.0004 \quad ,\\ \sin^2\theta_W &= 0.2242 \pm 0.0012 \quad ,\\ m_t &= 173 \pm 11 \pm 18\ \mathrm{GeV} \quad ,\end{aligned}$$

including the two-loop $\mathcal{O}(\alpha\alpha_s)$ QCD correction to m_t, where the first uncertainty is experimental and the second due to the unknown Higgs boson mass. This top quark mass value is in almost exact agreement with the CDF value, $m_t = 174\pm16$ GeV. The $\mathcal{O}(\alpha\alpha_s^2)$ threshold correction raises m_t by about +3 GeV. For the SM with general, non-doublet Higgs VEVs:

$$\begin{aligned}\sin^2\hat{\theta}_W(M_Z^2) &= 0.2318 \pm 0.0005 \quad ,\\ m_t &= 170 \pm 16\ \mathrm{GeV} \quad ,\\ \rho_0 &= 1.0004 \pm 0.0003 \quad ,\end{aligned}$$

where m_t is determined mainly by R_b. For the SM with S, T, U and doublet-only Higgs VEVs:

$$
\begin{aligned}
\sin^2 \hat{\theta}_W(M_Z^2) &= 0.2314 \pm 0.0004 \quad , \\
m_t &= 175 \pm 16 \text{ GeV} \quad , \\
S &= -0.15 \pm 0.28 \quad , \\
T &= -0.08 \pm 0.35 \quad , \\
U &= -0.56 \pm 0.61 \quad ,
\end{aligned}
$$

where the top quark mass here is determined by R_b. The CDF measured value of the top quark mass is the reference for $S = T = U = 0$. These fits lead to a picture consistent, within one standard deviation, with the minimal SM (where $m_t = 174 \pm 16$ GeV), with little room for non-Standard physics. Note in particular that the central value of S is equal to zero within one standard deviation, a significant change from the recent trend of S measurements, which had been more negative [41]. The best projected precision electroweak measurements will require an uncertainty in m_t of about 10 GeV to eliminate m_t as a significant source of uncertainty in radiative corrections analyses.

The effect of strong interactions in principle introduces uncertainties into electroweak calculations. Insofar as these effects are computable using perturbative QCD, the strong gauge coupling α_s must be known. Two distinct measurements have been deduced from the LEP data, both within the $\overline{MS}$ renormalization scheme and the mininal SM framework. The first is derived from the hadronic branching ratio R_{had} and the total Z width Γ_Z, excluding Γ_b; this yields $\hat{\alpha}_s(M_Z^2) = 0.124 \pm 0.006$. The second is derived from hadronic jet topologies from hadronic Z decays, yielding: $\hat{\alpha}_s(M_Z^2) = 0.123 \pm 0.005$. There are still significant (1-3σ) discrepancies between these results and the same $\overline{MS}$ coupling inferred from certain lower-energy measurements (DIS and b and c meson properties); the latter values are all lower than the LEP value. In the minimal SM with S, T, and U, the strong coupling $\hat{\alpha}_s(M_Z^2) = 0.103 \pm 0.011$ is considerably lower, because of the effect of γ_b in $\Gamma(Z \to b\bar{b})$ [4]. In the case of the hadronic contribution to the QED vacuum polarization (photon self-energy), the effect of low-lying resonances can be incorporated using a dispersion relation with the $e^+e^- \to$ *hadrons* data [5,42]. In the case of quark final states at LEP and SLC, QCD effects are included by perturbative computation or by forming quantities, such as $A_{LR}(Z)$, that are insensitive to strong interactions [43]. In hadron colliders (Tevatron, Sp$\bar{\text{p}}$S, HERA), QCD effects are calculated using perturbation theory, renormalization group techniques, and structure functions [44].

Status of Symmetries in Electroweak Gauge Interactions

C, P, CP : *Discrete, Global:* Quantum electrodynamics is known experimentally to conserve C and P separately. The electroweak SM connects C and P together in such a way that CP is conserved in electroweak gauge interactions, while C and P are separately violated [5,38]. P violation is used in atomic parity violation, polarized e-nucleus scattering, and the polarization asymmetry $A_{LR}(Z)$. C violation is measured by the forward-backward asymmetries $A_{FB}(Z)$ at the Z pole. The $\sin^2 \theta_W$ measurements from the two asymmetries should, by CP symmetry, be identical, and there is no clear evidence at present that this is not so. The 2.3σ discrepancy between the LEP $A_{FB}(Z)$ and SLC $A_{LR}(Z)$ measurements of $\sin^2 \theta_W$, if real, would be a signal of CP violation in electroweak gauge forces or of a new interaction.

B, L : *Continuous, Global:* Baryon and lepton numbers are exactly conserved in the SM, and there is no evidence of any B or L violation at present [4]. Quark mass mixing allows the transformation of baryons of one family to another, while leaving B fixed. The separate L family numbers, however, are conserved. The only evidence of lepton family mixing at present comes from various possible signals of neutrino oscillations; however, such effects are negligible in high-energy accelerator experiments. The electroweak gauge interactions respect the separate family B and L quantum numbers, with no contrary experimental evidence.

$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$: *Continuous, Local:* The electroweak gauge symmetry $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ accounts for the four electroweak gauge bosons and the relation of the weak charged and neutral currents mediated by the massive W and Z gauge bosons. Parity violation in both weak currents is predicted correctly, as is the relation of the W and Z gauge boson masses (see below). This symmetry is broken by the Higgs sector, with the $\mathrm{U}(1)_Q$ gauge symmetry of QED left unbroken. The exact unbroken QED symmetry implies a massless photon and conserved electric charge, both tested experimentally to high accuracy [4]. There is no positive evidence at present for a larger electroweak gauge group or new weak gauge bosons [4].

$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$: *Continuous, Global:* The global weak chiral symmetry is apparently an exact symmetry of the Higgs sector, broken spontaneously by the Higgs VEV down to the weak chiral custodial subgroup $\mathrm{SU}(2)_V$ (see below). Apart from the static Higgs VEV breaking of $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$, the radiative parameter S measures the dynamical, momentum-dependent breaking of $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ arising from loop corrections [5]. The present value of S shows no significant deviation from zero.

$\mathrm{SU}(2)_V$: *Continuous, Global:* The weak chiral custodial subgroup $\mathrm{SU}(2)_V$ is the vector subgroup of $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$. It is respected by the Higgs sector to high accuracy, as measured by the parameter ρ. The deviation from $\rho = 1$ is accounted for the large top-bottom quark and the $Z - W$ mass splittings. The residual deviation from unity, indicating a general, non-doublet Higgs sector, is zero at 1.33 standard deviations. The radiative parameters T and U measure the violation of $\mathrm{SU}(2)_V$ by loop corrections, beyond the minimal SM content [5]. They are both zero within one standard deviation.

GIM Family Symmetry: Continuous, Global: This symmetry rotates all up-type quarks into one another and all down-type quarks into one another. The electroweak gauge interactions respect this symmetry, preventing flavor-changing neutral currents (FCNCs);the quark mass matrix does not. This violation of GIM symmetry gives rise to FCNCs, but at the loop level only, and suppressed by $G_F^2 m_{q'}^2 m_q^2$ [5]. All observed FCNCs (K, D, and B mesons) are consistent with the minimal Cabibbo-Kobayashi-Maskawa quark mass matrix mixing [4].

Hypothetical Symmetries: These include *new gauge groups* and *gauge bosons, supersymmetry,* and *technicolor.* The first and last are local symmetries, while the second is global. There is at present no evidence for new weak gauge bosons, supersymmetric partners of Standard Model states, or technifermions and technicolor gauge bosons [4]. The last two would have radiative effects in weak interactions; supersymmetry small to negligible, technicolor generally moderate to large. The lack of significant deviation in present data from the minimal SM tends to favor supersymmetry, but only negatively, by the absence of any effect [45]. Consistent technicolor theories respecting the electroweak and FCNC precision constraints have yet to be constructed, although a several general schemes have been proposed [46]. Such technicolor theories would have to produce almost no $\mathrm{SU}(2)_V$ custodial breaking, beyond the top-bottom quark mass splitting, while having either small technifermion sectors or special cancellations to guarantee $S \simeq 1$ or smaller.

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